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ECG 646: Photovoltaic Devices and Systems

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History, Evolution, and Future of PV Cells

The practice of harvesting and making use of energy that comes from the sun has been a gradual process which began over 170 years ago when the photovoltaic effect was first observed. A material or device is said to be *photovoltaic* if it can convert the energy contained in light into an electrical voltage/current. The phenomenon was first observed by a 19-year-old French physicist named Alexander Edmund Becquerel in 1839 when he illuminated a metal electrode in a concocted solution and a voltage was generated in the solution as a result of the illumination [2]. During the late 1870s through experimentation with the photovoltaic effect in selenium and other solids, Professor William Grylls Adams and his student Richard Evans Day "discovered that it was possible to convert solar energy directly into electricity without heat [7]." In other words, they discovered that light-generated current was a unique type of electrical current which was not the same as the already-known thermally generated current. Their work led to the development of selenium cells with 1-2% efficiency, adopted by the then-emerging photography industry for photometric light meters. They are still used for this purpose today [2].

In 1883, an American inventor named Charles Edgar Fritts constructed a solar module "by coating a wide plate of copper with selenium and then topped it with an extremely thin semi-transparent layer of gold leaf [7]," also which had an efficiency of just around 1%. Though the current was constant, continuous, and of considerable force as reported by Fritts, these modules were not commercially feasible due to the high cost of both gold and selenium. Further work by Albert Einstein in the first decade of the twentieth century put light energy and the photovoltaic effect into a new perspective which was tangible and understandable in scientific terms, but to no avail. The conversion efficiency of cells remained at 1% or less for the next 50 years. Despite the half-century long struggle faced by those studying photoelectricity at the time, there was still optimism. Maria Telkes, a Hungarian-American scientist from MIT who worked on several solar energy projects throughout the twentieth century stated, “Personally, I believe that photovoltaic cells will be the most efficient converters of solar energy if a great deal of research and development work succeeds in improving their characteristics [7].” This optimism would not come up empty, as the time which remained in the twentieth century and the start of the twenty-first century would see enormous strides forward in the realm of photovoltaics and the conversion of light (that which comes from the sun of the utmost importance and emphasis) into electricity.

In April of 1954, New Jersey’s Bell Telephone Laboratories released a silicon solar cell which converted light to electrical energy with 6% efficiency [7], which scientists believed could be raised to 10% without any innovation. By 1956, toys and radios began implementing this technology to power electronics inside. At this time, the cost of a one-watt solar panel was $300, which was far beyond unaffordable for the average person. Through the 1950s and 1960s efficiency increased to about 14% as space programs began to rely more heavily on solar power for satellites. In the 1970s, funded by Exxon Corporation, Dr. Elliot Berman designed a cheaper solar module and a cheaper manufacturing technique which brought the cost of solar power down to just $20/watt. This innovation paved the way for applications on the ground, such as solar cells used to power homes, which we have today.

Currently, there are several different types of solar cells outside the realm of silicon, each with their own set of benefits and drawbacks. The main tradeoff we see today is the tradeoff between efficiency and price. If a consumer is looking for the cheapest solution to a problem, they will likely want to go with dye-sensitized solar cells, which are around 12% efficient, but very cheap. Another very low cost, and also relatively low efficiency, cell type is the organic solar cell. Organic solar cells have seen a significant increase in efficiency over the last year (since 2019) improving from 15.6% efficiency in 2019 to 17.4% efficiency in 2020. Moving forward with the production of solar cells, organic solar cells are predicted to become increasingly important and common due to their low cost [3]. According to *Synergy Files*, a news and information website for renewable energy, the majority of cell types are in the mid-price range and the mid-efficiency range as well. For example, the following cell types all have efficiencies between 22.1% and 26.1% as of 2020:

- Thin-Film Cadmium Telluride Cells (22.1% efficient)
- Polycrystalline Cells (22.8% efficient)

- Thin-Film CIGS Cells (23.4% efficient)
- Un-stabilized Perovskite Cells (25.2% efficient)
- Monocrystalline Cells (26.1% efficient)

The 22.8% efficient polycrystalline cell is the most common type of solar cell on the market to date, and it is the cell type used to construct most residential solar panels. Consumers seem to find the cost-efficiency tradeoff of polycrystalline solar panels to be the best-case scenario for most purposes. Nonetheless, monocrystalline solar panels are also available on the market. They are sleeker, have a black tint to them (unlike the blue tint of the polycrystalline), and have significantly higher efficiency than their polycrystalline counterparts. The polycrystalline cells are manufactured by melting many small silicon fragments together. The result of the polycrystalline structure is less movement of free carriers, thus limiting efficiency. The monocrystalline cells are created using single-crystal silicon, and there is more freedom for carriers to move resulting in improved efficiency.

The most efficient of solar cell types manufactured today are, as expected, in the highest price bracket, so they are not used in residential solar panel manufacturing. Rather, they are mostly used in commercial solar panels or in spacecraft, where cost is not of the utmost importance. The upper range of solar cell efficiency consists of the following technologies:

- Tandem Perovskite Cells (28% efficient)
- Gallium Arsenide Cells (30% efficient)
- Multi-Junction Solar Cells (**39% efficient**)

Before jumping into the eye-catching high efficiency of multi-junction solar cells, it should be noted that GaAs cells are the type of cells **most commonly used** in spacecraft. The manufacturing process for these cells is an expensive one, so their cost is very high. However, according to an article in *PV Magazine*, “a team at the U.S. National Renewable Energy Laboratory (NREL) has come up with a new process that would reduce the production cost” of GaAs cells, which would lower the cost and potentially make the high-efficiency technology available to the general population. In the same article, it is mentioned that the expense is contingent upon the two-hours-per-cell required production process. The NREL has made strides while using a new process which can produce a cell in less than a minute, but efficiency has taken a hit. The current battle is to maintain efficiency while improving this incredibly long cell production time.

One characteristic of solar cells which results directly in limited efficiency is the fact that different semiconductor materials produce electrical current in response to different wavelengths of light. The light earth receives from the sun contains a broad spectrum of wavelengths, only a small range of which can be captured by a single-junction solar cell. Scientists came up with the clever idea of multi-junction cells which are composed of multiple different materials, carefully designed and selected to respond to different ranges of the solar spectrum. These different junctions make up layers of the multi-junction solar cells such that one material, presumably the top of the stack of materials, can absorb a higher energy part of the spectrum and the other layers can absorb the lower energy parts of the spectrum. It is important to note that the thickness of each layer must be designed such that each layer generates the same current, since they are series connected. Though lab conditions cannot be met in the real world, lab examples of multi-junction cells under concentrated sunlight have converted light to electricity with up to 46% efficiency. The GaAs cells mentioned previously are just one type of multi-junction cell technology. Just to reiterate, the heart of the battle for scientists and engineers who are focused on PV technology and renewable energy is the attempt to improve manufacturing time and cost. Once the time required to manufacture a single multi-junction cell is reduced significantly, the cost will be reduced also, and we may see more multi-junction technology in every-day applications.

Technologies that require a long manufacturing time are not the only technologies with efficiency problems. Other solar cells deal with issues such as reflectivity, limited sun energy concentration, shading, and contamination by nature (dirt or dust). For example, residents who want to be sure that they are getting the most out of their solar panels need to make sure they keep them clean. If the surface of a solar panel is covered in dust, the sun-generated current in the cells is decreased dramatically, resulting in a huge decrease in the output power of the system as a whole. The cost of maintenance and cleaning is intangible, but a cost comparison would likely show that taking the time and purchasing the materials required to clean up solar panels every so often would not outweigh the amount of power lost when the panels are covered in dirt and not performing at their peak potential. Also, when panels are installed in residential areas, the installation team should do their best to install the panels where the effects of shading will be minimized. A shaded panel, especially one with a limited number of bypass diodes (which increase cost), does not output nearly as much power as one with no shading. The shading reduces the amount of solar insolation to which the panel is exposed, thus greatly decreasing the sun-generated current of the panel, be it that sun-generated current and solar insolation exposure are proportional. The only cost associated with shade avoidance is the cost of area lost if a house has a large area on the roof which is susceptible to shading throughout the year.

As far as reflectivity and sun concentration limitations go, scientists have made efforts to make use of their effects to benefit the efficiency of solar cells in a number of ways. One solution that has been tested and proven to work is texturizing or "roughening up" the surface layers of solar cells to reduce the effects of reflectivity and achieve better light trapping and absorption of solar spectral content [9]. Experimentation has been conducted yielding proof that solar cells with textured front and back contacts are more efficient than cells with only one side textured, and these single-sided texturized cells are more efficient than those with no roughening or texturization at all. For example, the absorptance, reflectance, and transmittance of Corning Eagle Zinc Oxide Amorphous Silicon (CE/ZnO/a-Si/air) structure multi-junction cells with no surface roughness were measured against a number of other compositions of multi-junction cells and their performance in these categories. The worst of the cells with no roughness displayed 21.15% absorptance, 44.64% transmittance, and 34.21% reflectance. The best of the cells with the finest texturization showed an amazing 74.7% absorptance, just 16.7% transmittance and a minute 8.59% reflectance. The enormous difference in performance is great, but the texturization of cells is an expensive process, which greatly increases the cost of these efficient cells.

Since the concentration of sunlight requires a lot of hardware and special equipment, the cost-benefit analysis of the addition of this hardware to concentrate sunlight and only slightly improve efficiency proves unsatisfying for residents who would like to see improved efficiency in solar panels. However, a new type of module which displays improved production has been introduced known as the bifacial solar module. The bifacial solar module is a type of solar power generating module which contains solar cells both on the front and the back of the panel so that it can accept direct sunlight on the front and reflected sunlight on the back, resulting in an overall greater power production than a one-sided panel would. According to a 2018 *Solar Power World* article on bifacial solar modules [10], "some bifacial module manufacturers claim up to a 30% increase in production just from the extra power generated from the rear." This is a big deal because many high-cost techniques and technologies only slightly improve efficiency. The bifacial solar panels form arrays which can produce more energy in the same amount of square footage as a unifacial or traditional solar panel array would, making them cost-effective and attractive to consumers.

Of all the proposed methods discussed previously, bifacial solar module construction and implementation seems to be the leader in increased productivity for the cost at the moment. However, the researchers, scientists, and engineers working at NREL and elsewhere on reducing the time taken to manufacture high-efficiency multi-junction cells are also on the rise. Though they currently fight with the tradeoff in the loss of efficiency for improved manufacturing time, their efforts will continue, and the bifacial module will likely see increasing competition in the years to come. The United States federal and state governments have increasingly discussed the importance and likely future dependence on solar power moving forward as a nation, so the photovoltaic research teams will be hard at work to make the most efficient solar panels possible for the most reasonable cost. We have seen steady increases in the country's overall reliance on solar power for its energy needs in the past few decades and will almost certainly continue to see that trend for the decades to come. As solar power remains the largest source of untapped potential the earth has ever seen, it would be ludicrous to ignore the possibilities. As it stands, in a single day, the sun supplies the earth with more energy than our entire yearly energy consumption as a planet [2]. Right now, scientists and engineers have discovered and designed ways to repurpose only a minute fraction of that energy. As technology continues to develop, the earth will continue to rely more and more on solar power.

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